· Chapter IV
Novel Wavelength Converter by using Nonlinear Polarization Rotation of Electroabsorption Modulator

4.1 Introduction

In DWDM system, all-optical wavelength conversion is one of the key technologies. It solves the problem of wavelength channel contention, and hence improves the scalability of optical network.

So far, several approaches have been proposed and investigated to achieve all optical wavelength conversion. In silica fiber, Kerr effect has subpicosecond response and has been applied for the wavelength conversion, although quite large optical power is required to induce large phase shift due to its low efficiency [1] [2]. Compared to fiber, a semiconductor optical amplifier (SOA) is superior in efficiency by using cross gain modulation (XGM), and very low power, a few or submilliwatt, is required for the conversion [3] [4]. However, its response time is in the order of a few tens of picoseconds. The four wave mixing is also applied in the SOA based wavelength conversion with inherently fast response [5]. However, it is also typically of low efficiency.

Recently, wavelength conversion based on electro-absorption modulator (EAM) has been proposed by utilizing cross-absorption modulation (XAM) [6] and cross-phase modulation (XPM) [7] and high-speed application have been demonstrated [8][9]. The EAM has the merits of short recovery time under reverse bias (typically 10ps), high stability and easy integration with other devices, especially, lasers. XAM, however, suffers from large absorption loss and poor extinction ratio. Up to now, since bulk electro-absorption modulators were used in almost all experiments, very large signal power (>+15dBm) was usually required. To solve these problems, a novel all-optical wavelength conversion scheme based on XPM in multiple-quantum-well electro-absorption (MQW-EA) modulators was proposed [10] [11]. Furthermore, we also successfully fabricated the Al-containing quantum well EAM by MOVPE which has larger photo-induced refractive index change due to its larger conduction band offset (~0.5eV) and stronger confinement effect of the exciton than those of InGaAsP [12] [13].

4.2 Nonlinear Polarization Rotation in Electroabsorption modulator

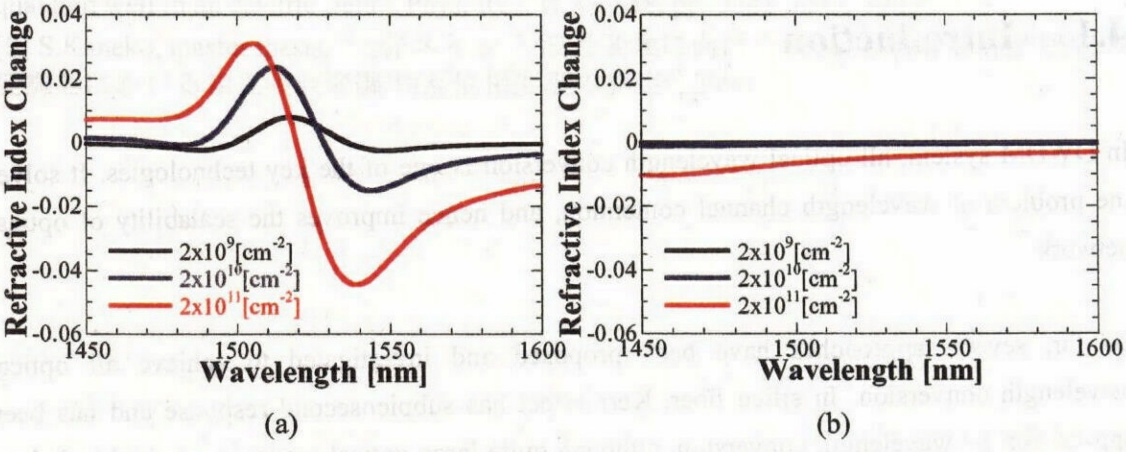

Fig.4. XPM for (a) TE and (b) TM

In MQW, the transverse electric (TE) and transverse magnetic (TM) modes always shows different optical parameters, such as refractive index and absorption coefficient, due to the degenerate of the band energy for heavy hole and light hole. The gain spectrum in SOA and absorption spectrum in EAM both show difference between TE and TM mode. Moreover, the cross absorption modulation and cross phase modulation in semiconductor are also different.

Fig.4.1 shows the difference XPM for the probe light in an EAM while another pump light injected into the same EAM simultaneously. One can see that at the same wavelength, the XPM for TE mode has larger change than that for TM mode. By using this, the polarization state of the probe light can be changed by the pump light, which is schematically shown in Fig.4.2

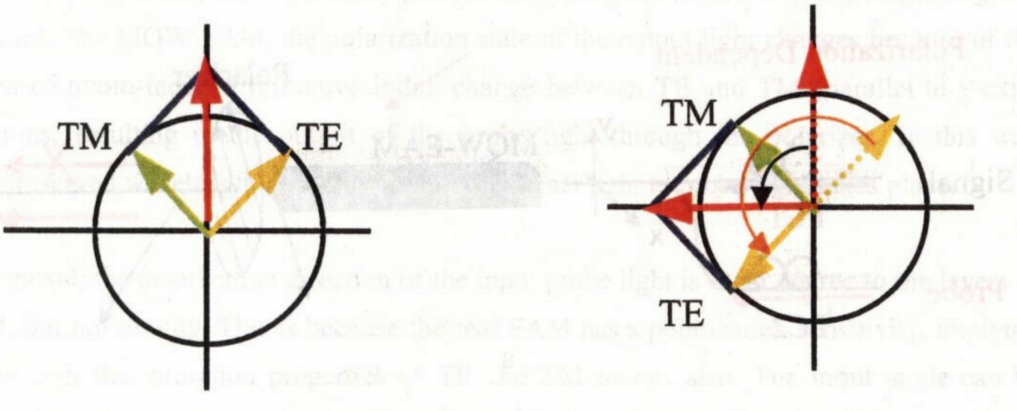

Fig.4. 2 schematic of the polarization

The input light is composed of TE and TM mode with the same intensity and +/- 45° angle with the polarization state. When the pump light is injected into the device, both of the TE and TM modes undergo phase shift. Due to the difference of the XPM between them, the phase shift for TE mode can be 180° larger than that of TM mode, resulting in 90 rotation of polarization state for the output light. Note that for simplification, the difference of XAM is not taken into account.

The nonlinear polarization rotation has been well investigated in SOA [14] [15] and the polarization switches, and wavelength converters based on the nonlinear polarization rotation (NPR) in optical signal processing applications are receiving considerable interest [16] [17].

However, as far as I am concerned, no report has been reported on the NPR in EAM devices except our group. The latest research is carried out in [18]. The other similar research is the XPM investigation and its application in wavelength conversion in KDDI. Even though in their research, only TE mode is taken into account.

In 1998, Dr. Kato investigated the difference of XPM between TE and TM numerically [14], and then proposed a novel wavelength converter based on this. Later, the static wavelength conversion performance was demonstrated by using the InGaAsP MQW EAM. In this work, we develop the concept, change the material into InGaAlAs, further investigate the scheme and demonstrate its dynamic operation.

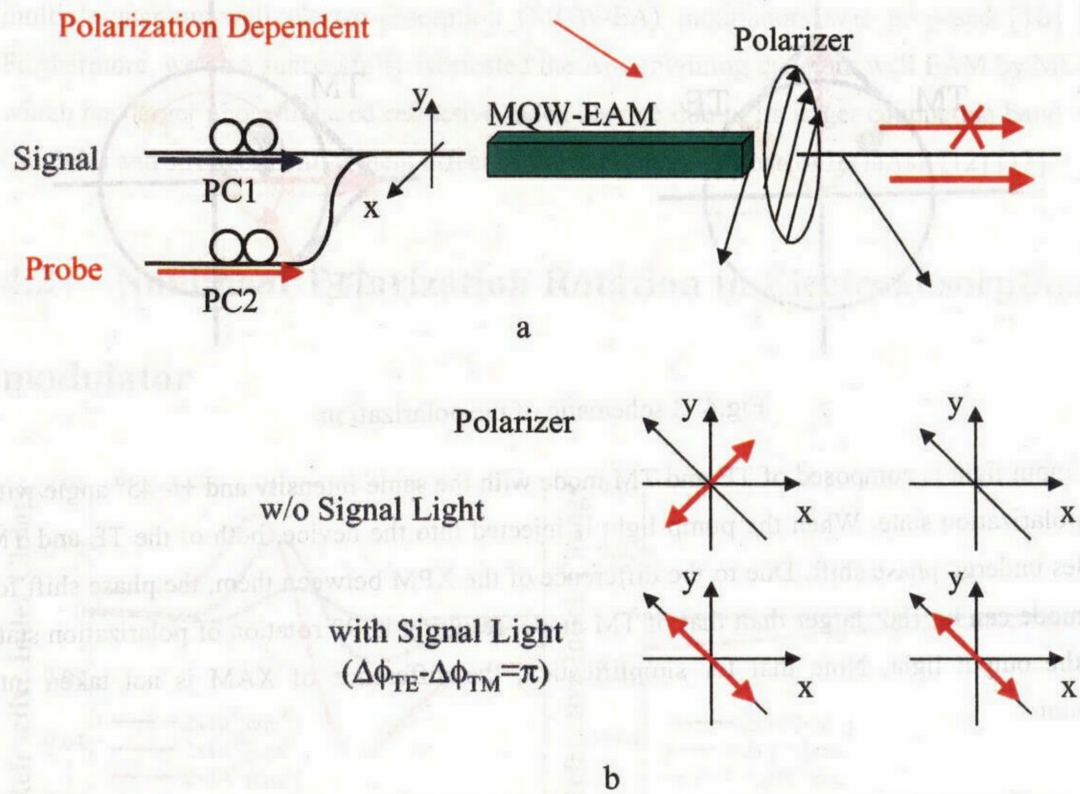

Fig.4. 2 Principle of the wavelength conversion using the polarization dependence of XPM in MQW-EAM.

4.3 Operation Principle of the Wavelength Converters based on Nonlinear Polarization Rotation in Electroabsorption Modulator

The configuration of the proposed wavelength conversion is illustrated in Fig.4.2 (a). The polarization of the signal light is TE polarization, which is parallel to x-axis. Shown in Fig.4.2 (b) is the change of the polarization state of probe light by the signal light. When no signal light comes into the MQW EAM, the output of the probe light from MQW EAM is linearly polarized and tilted by 45° with respect to x-axis by polarization controller (PC2). When the signal light is launched into the MQW-EAM, the polarization state of the output light changes because of the difference of photo-induced refractive index change between TE and TM (parallel to y-axis) polarizations, resulting in the output of the probe light through the polarizer. In this way polarity-preserved wavelength conversion from the signal light to probe light takes place.

In the proposal, the polarization direction of the input probe light is at 45 degree to the layers of the EAM, but not exactly. This is because the real EAM has a polarization sensitivity, implying a difference in the saturation properties of TE and TM modes also. The input angle can be carefully adjusted to compensate for this, thus achieving the output probe light with linear polarization. Nevertheless, even the output light is not linearly polarized, the converter can still be switched from constructive into destructive, and vice versa.

Unlike the ultrafast nonlinear interferometer (UNI) in which the probe TE and TM pulses are temporally separated and then combined after the interaction with the pump pulse by the polarization maintaining fiber, we here use the continuous wave as the probe light and both the TE and TM modes have phase shift due to the photo-generated carrier.

4.4 Static wavelength conversion

The EAM is composed of 10 sets of InGaAlAs/InGaAlAs MQW with the well width of 10nm and barrier width of 5nm, sandwiched by separate-confinement heterostructure (SCH) layers. The whole structure was grown by metal organic vapor phase epitaxy (MOVPE).The photocurrent peaks for the TE and TM mode are 1490nm and 1440nm respectively. The device length is 270μm.

Fig.4.3 shows the static electrical modulation characteristics under input power of 0dBm at 20°C. The extinction ratio for the TE mode is quite larger than that of the TM mode due to the difference of the absorption edge for the TE and TM mode. The transmission difference between them is not so large (about 5 dB) because the photocurrent peak wavelength difference is only about 50 nm.

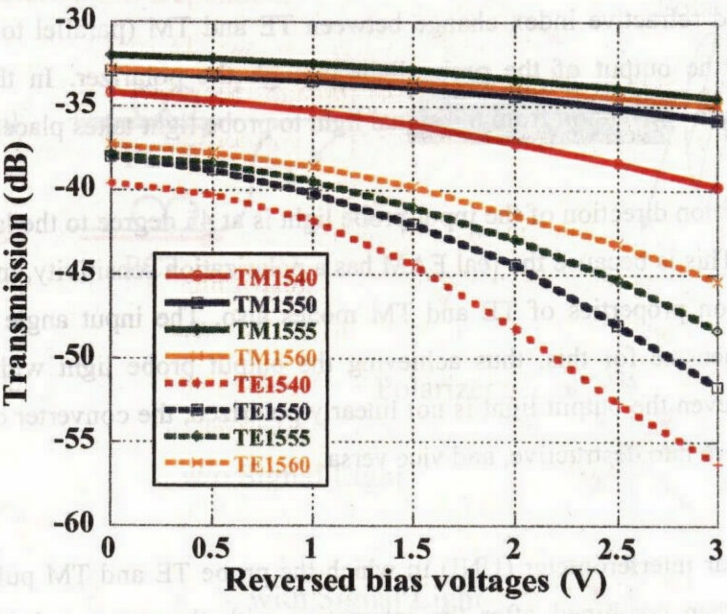

Fig.4.3 Electrical modulation of the EAM based on sample #3694.

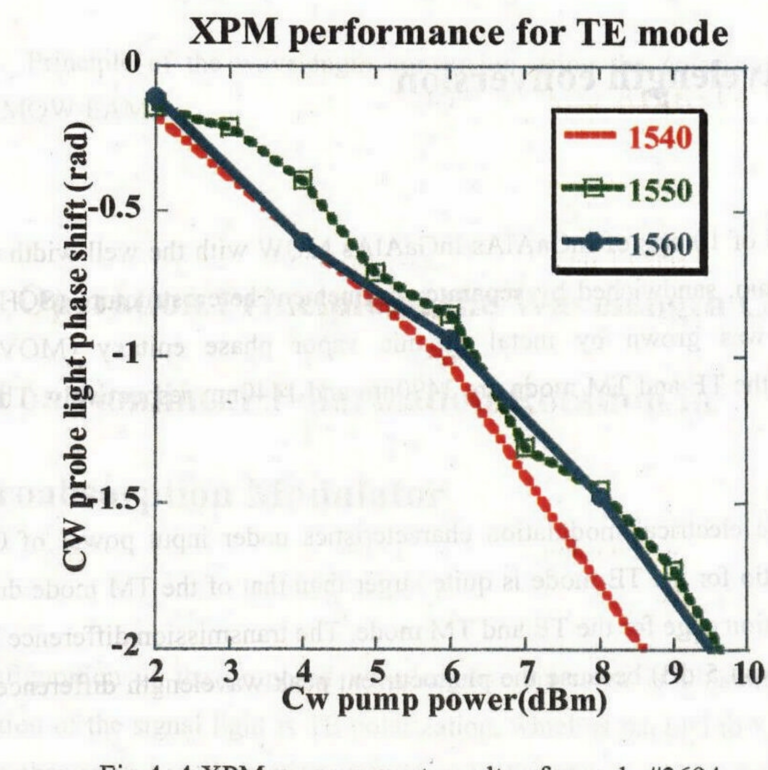

Fig.4. 4 XPM measurement results of sample #3694

The XPM properties for TE mode have also been measured by Fabry-Perot method, which are shown in Fig.4.4. The wavelength of the CW pump power is 1530nm and the average power of the probe light is 4dBm. The wavelength of probe light varies from 1540nm to 1560nm. We can know from this figure that the absolute value of the phase shift increases almost linearly in the range of the pump power. Typically, for π shift, the pump power is about 10dBm including the coupling loss of 8dBm between the tapered fiber and the EAM.

Fig.4.5 shows the experiment setup for this measurement. The CW probe light wavelength was fixed at 1555nm. The power of co-propagating CW signal light was set at 0dBm with the wavelength varying from 1550nm to 1560nm to obtain both upward and downward conversion. The polarization of the probe light is adjusted by a Babinet-Soleil polarization controller (BSPC). Due to the absorption difference for TE and TM mode in the EAM, the input angle did not have to be 45° with respect to x-axis and the PC1 was adjusted to optimize the conversion efficiency. The bias voltage of EA modulator varied from 0V to -2V. The measured insertion loss was 24dB, and propagation loss was 3dB by Fabry-Perot Etalon method. So the coupling loss between the tapered fiber and the device is about 10dB for each facet in this experiment.

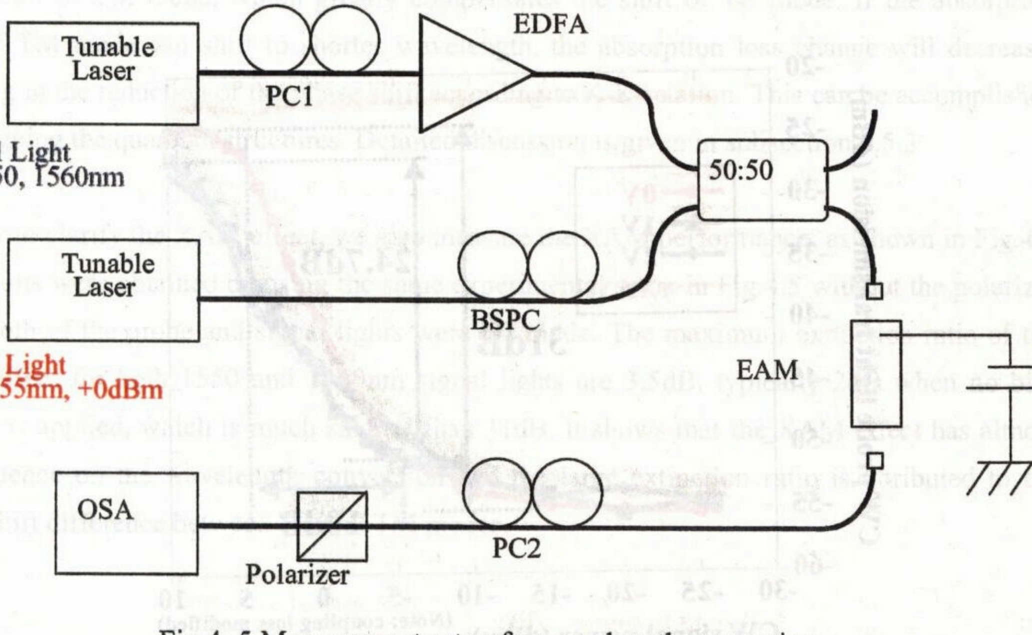

Fig.4. 5 Measurement setup for wavelength conversion.

PC: polarizer controller, BSPC: Babinet-Soleil polarization controller, OSA: optical spectrum analyzer

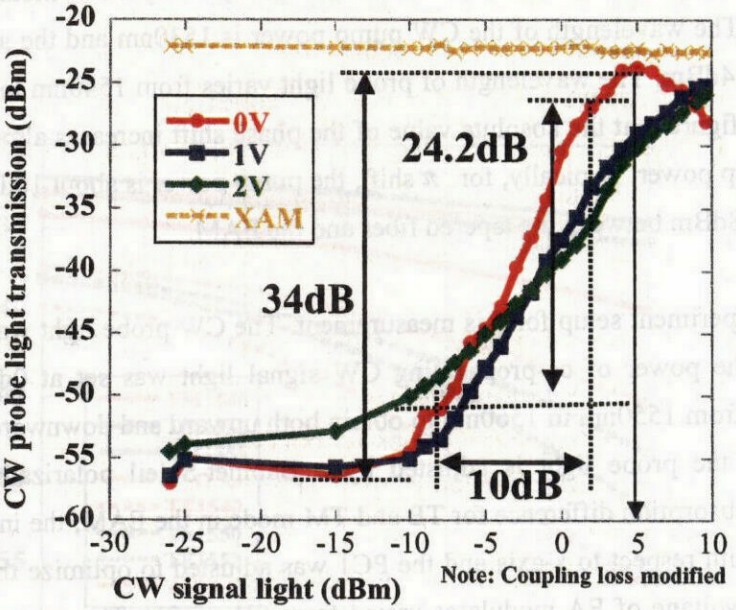

Fig.4. 3 Wavelength conversion from 1550nm to 1555nm.

The solid lines are conversions at different bias voltages; the top dotted line is for XAM.

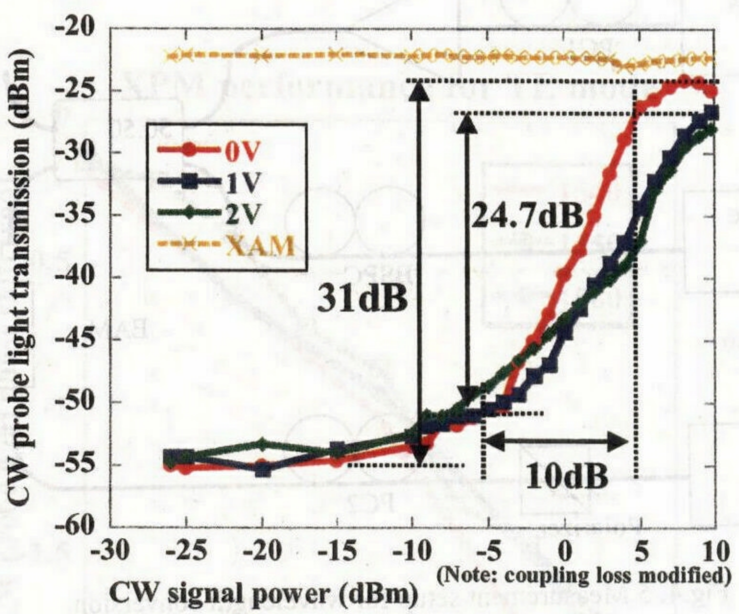

Fig.4. 4 Wavelength conversion from 1560nm to 1555nm

The solid lines are conversion at different bias voltages; the top dotted line is for XAM result in the same experiment setup

Fig.4.6 and Fig.4.7 show the wavelength conversion results from both 1550nm and 1560nm to 1555nm. When there is no bias, for π phase shift, the input powers are only +5dBm (coupling loss included) for upward conversion and +8dBm (coupling loss included) for downward conversion while the extinction ratios are 34dB and 31dB, respectively. These are great improvements from the previous one [3]. The enlargement of extinction ratio, furthermore, is realized; as shown in the figures. For example, for the upward conversion, the input extinction of 10dB (form –8dBm to +2dBm) is improved to 24.2dB (from –64.1dBm to –39.9dBm). Note that the photocurrent peaks for TE and TM wavelength are quite shorter than the previous ones. There is potential to decrease the input power by shifting the TM peak to a shorter wavelength. These two figures also show that, when the bias voltage increases, the input power for π phase shift becomes larger. This matches the results in ref. [7]: the larger the bias voltage, the smaller the XPM phase shift when the input power is fixed.

Note that the pump power is still much larger than that in Fig.4.4. One reason is that, here we use longer pump wavelength of 1550nm and 1560nm instead of 1530nm. Shorter pump light wavelength leads to smaller input power for π shift. Another reason is due to the considerable phase shift of TM mode, which greatly compensates the shift of TE mode. If the absorption peak of TM mode can shift to shorter wavelength, the absorption loss change will decrease, resulting in the reduction of the phase shift according to K-K relation. This can be accomplished by designing the quantum structures. Detailed discussion is given in subsection 4.5.3

In order to clarify the XAM effect, we also measure the XAM performance, as shown in Fig.4.8. The results were obtained by using the same experimental setup in Fig.4.5 without the polarizer PC2. Both of the probe and signal lights were TE mode. The maximum extinction ratio of the XAM effect for both 1550 and 1560nm signal lights are 3.5dB, typically 2dB when no bias voltage is applied, which is much smaller than 31dB. It shows that the XAM effect has almost no influence on the wavelength conversion and the large extinction ratio is attributed to the phase shift difference between TE and TM modes.